



## SYSTEM AND METHOD FOR OPTICALLY INTERCONNECTING MEMORY DEVICES

### TECHNICAL FIELD

This invention relates generally to structures for interconnecting memory  
5 devices. More specifically, the present invention relates to methods and apparatus for  
communicating with memory devices while eliminating cross talk and decreasing noise.

### BACKGROUND OF THE INVENTION

A main focus of the contemporary semiconductor industry is the creation  
of smaller and more efficient memory devices and memory modules. These efforts are  
10 often frustrated by cross talk and signal noise. Cross talk is an inductive effect which  
can arise when a variable current flows through a conductor. Variable current creates a  
corresponding variable magnetic field surrounding the conductor capable of inducing a  
disruptive signal in any adjacent conductors passing through the magnetic field. As a  
consequence, the placement of conductors must be carefully engineered in order to  
15 maintain suitable distances of separation between the conductors to minimize the effects  
of cross talk.

Similarly, noise is interference that results in the corruption of electrical  
signal integrity. Noise can be caused by any of a variety of different sources, including  
radio waves and adjacent electrical wires or magnetic fields. Common techniques for  
20 ameliorating noise include shielding conductors and spacing conductors from each  
other, and from other electrical components.

Overall, the necessity of such careful considerations in shielding and  
spreading out conductors to minimize the effects of cross talk and noise complicates  
efforts to create cheaper and smaller memory devices.

25 A common memory device, such as a dynamic random access memory  
(DRAM), includes a semiconductor on which electronic circuitry (*i.e.*, an integrated  
circuit) is fabricated. The chip is physically and electrically attached to a chip package,  
which is a protective container, such as a plastic dual-in-line package (DIP) or printed  
circuit board to which the chip is coupled. The chip is typically electrically coupled to

the chip package by forming electrical connections between bonding pads on the chip and leads or pins on the chip package.

As the functionality of memory devices increases, the complexity of the electronic circuitry typically increases along with the required number of pins on the chip package required to support this increased functionality. For example, as the storage capacity of a DRAM increases, more address pins are required to access the data stored in the DRAM. To couple the DRAM to a circuit board, each pin must be electrically coupled to a conductive trace in a control, address or data bus. As the number of pins on the DRAM increases, the corresponding spacing between pins and conductive traces decreases, which heightens the potential for cross talk and noise on the control, address and data busses.

In a typical application, a plurality of DRAMs are mounted on a circuit board to form a memory module. Each DRAM receives address and control signals through address and control terminals on the circuit board, and has a data bus coupled to a corresponding data terminals on the circuit board. Typically, the memory module has a data bus that is M bits wide, where M is an integer multiple of N, which is the width of the data bus of each DRAM. Each DRAM on the module provides N of the M bits in response to common address and control signals applied to all DRAMs on the module. For example, a typical memory module includes 8 DRAMs each having an 8 bit wide data bus to form a 64 bit wide data bus on the memory module. Another typical memory module includes 9 DRAMs, each having an 8 bit wide data bus to form a 72 bit wide data bus on the memory module with 8 bits that function as error checking and correction bits.

Figure 1 is a simplified block diagram of a DRAM 100 including an address decoder 102 that receives address bits A0-AX on an address bus ADDR and decodes these address bits and applies decoded address signals 104 to a memory-cell array 106. The memory-cell array 106 includes a plurality of memory cells (not shown) arranged in rows and columns, each memory cell storing a bit of data. The data stored in the memory cells is accessed in response to the decoded address signals 104 from the address decoder 102. A read/write circuit 108 is coupled to the memory-cell array 106

through an internal data path 110 and is coupled to an external data bus DATA of the DRAM 100. In the example of Figure 1, the data bus DATA includes 8 external terminals over which data bits DQ0-7 are transferred to and from the DRAM 100.

As discussed above, however, the data bus DATA can include more terminals, such as 32 terminals, to transfer a corresponding number of data bits. As the number of terminals increases, the spacing between the terminals on the data bus DATA decreases, increasing the risk of cross talk and noise. The DRAM 100 also includes control logic 112 that receives a plurality of control signals applied on an external control bus CONT. In response to the control signals, the control logic 112 generates a plurality of control and timing signals 114 to control the timing and operation of the address decoder 102, memory-cell array 106, and read/write circuit 108 during operation of the DRAM 100.

In operation, an external circuit (not shown) such as a memory controller applies address, control, and data signals to the DRAM 100 over the address bus ADDR, control bus CONT, and data bus DATA, respectively, to control the operation of the DRAM. During read operations, the external circuit applies a read command to the DRAM 100 in the form of appropriate address signals on the address bus ADDR and control signals on the control bus CONT. In response to the applied address signals, the address decoder 102 accesses addressed memory cells in the memory-cell array 106 and applies the read data stored in the addressed memory cells over the internal data path 110 to the read/write circuit 108 which, in turn, places the read data on the data bus DATA as read data bits DQ0-7. The control logic 112 generates the appropriate control and timing signals 114 to control the address decoder 102, memory-cell array 106, and read/write circuit 108 during the read operation.

During write operations, the external circuit applies a write command to the DRAM 100 in the form of appropriate address signals and control signals on the ADDR and CONT buses, respectively, and also applies write data bits DQ0-7 on the data bus DATA. Once again, in response to the applied address signals, the address decoder 102 accesses the addressed memory cells in the memory-cell array 106. The read/write circuit 108 transfers the applied write data bits DQ0-7 over the internal data

path 110 and into the addressed memory cells in the memory-cell array 106. The control logic 112 operates during write operations to generate the appropriate control and timing signals 114 to control the address decoder 102, memory-cell array 106, and read/write circuit 108.

5           In both of the read and the write operations, considerable potential for cross talk and noise exists as electrical signals are coupled to and from the DRAM through the address bus ADDR, the control bus CONT, and the data bus DATA. This is exacerbated as the number of terminals on these busses increases, and the spacing between the terminals is necessarily decreased.

10           There is thus a need to decrease the density of busses coupling electrical signals to and from the pins of a DRAM to lessen the potential for cross talk and noise, without reducing the number of pins on the DRAM.

#### SUMMARY OF THE INVENTION

          According to one aspect of the present invention, a memory device  
15 includes a semiconductor substrate including memory circuitry. The memory circuitry includes an address decoder coupled to an address converter formed in the substrate. The address converter is operable to receive and convert optical address signals into corresponding electrical address signals to be applied to the address decoder. Additionally, the memory circuitry includes a read/write circuit coupled to a data  
20 converter formed in the substrate. The data converter is operable to receive and convert optical data signals into corresponding electrical data signals to be applied to the read/write circuit and to receive and convert electrical data signals into corresponding optical data signals. A control circuit is coupled to a control converter formed in the substrate. The control converter is operable to receive and convert optical control  
25 signals into corresponding electrical control signals to be applied to the control circuit. In addition, a memory-cell array is coupled to the address decoder, control circuit, and read/write circuit.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a functional block diagram of a conventional memory device.

Figure 2 is a functional block diagram of a memory device including control, address, and data converters according to one embodiment of the present invention.

Figure 3 is a block diagram of a memory module having a plurality of memory devices according to one embodiment of the invention.

Figure 4 is a block diagram of a memory module having a memory hub and a plurality of memory devices according to one embodiment of the invention.

Figures 5 A-B are cross-sectional views of a memory module having a memory hub and a plurality of memory devices according to one embodiment of the invention.

Figure 6 is a block diagram of a computer system containing several memory modules such as illustrated in Figure 4 according to one embodiment of the invention.

## DETAILED DESCRIPTION OF THE INVENTION

Figure 2 is a functional block diagram of a memory device 200 that receives control signals, address signals, and data signals optically, as will be explained in more detail below. In the simplified block diagram of Figure 2, the memory device 200 is a double data rate ("DDR") DDR SDRAM, which performs an event, such as latching data, with each transition of a clock signal. However, the principles described herein are applicable to any memory device, such as conventional asynchronous DRAMs and synchronous DRAMs (SDRAMs), as well as packetized memory devices like SDRAMs and RDRAMs, and are equally applicable to any integrated circuit receiving and transmitting signals to and from itself. In the following description, certain details are set forth to provide a sufficient understanding of the present invention, but one skilled in the art will appreciate that the invention may be practiced without these particular details. In other instances below, the operation of well known components have not been shown or described in detail to avoid unnecessarily obscuring the present invention.

The memory device 200 formed on a semiconductor substrate 201 includes an address converter 205, including a plurality of optical receivers formed in the substrate, which receives optical address bits A0-AX from an external optical address bus ADDR. Where mentioned, the term optical receiver should be understood to include any device capable of receiving an optical signal, for example optical Darlington transistors and optical field effect transistors. The optical address bits A0-AX are translated in the address converter 205 into corresponding electrical bits AO-AX, which are coupled to an address decoder 204 and decoded into corresponding electrical address bits. The address decoder 204 subsequently applies decoded address signals 206 to a memory-cell array 208. The memory-cell array 208 includes a plurality of memory cells (not shown) arranged in rows and columns, each memory cell storing a bit of data. The data stored in the memory cells is accessed in response to the decoded address signals 206 from the address decoder 204. A read/write circuit 54 is coupled to the memory-cell array 208 through an internal data path 55 and is optically coupled to an external optical data bus DATA of the memory device 200 through a data converter 211, which includes a plurality of optical receivers and transmitters formed in the substrate 201. Where mentioned, the term optical transmitter should be understood to include any device capable of transmitting an optical signal, including for example, vertical cavity surface emitting lasers such as described in U.S. patent 6,356,573 to Jonsson et al., which is incorporated herein by reference. The address converter 205 and the data converter 211 may both be formed in the same side of the semiconductor substrate as the address decoder 204, the memory cell array 208, and the read/write circuit 54.

The optical data bus DATA has a bandwidth enabling it to transfer 32 respective data bits DQ0-31 along with a data strobe signal DQS to and from the data converter 211. In a write cycle, the optical receivers in the data converter 211 receive optical data bits DQ0-31 and translate them into corresponding electrical signals, which are then coupled to respective data input/output ports (not shown) on the read/write circuit 54. In a read cycle, data bits DQ0-DQ31 are applied to the data converter 211 by the read/write circuit 54 over respective input/output ports on the read/write circuit 54. At the data converter 211, the bits DQ0-DQ31 are translated into corresponding optical

bits DQ0-DQ31 and transmitted to the optical bus DATA. The read/write circuit 54 outputs the DQS signal through an optical receiver in the data controller 211 during read operations to allow an external controller (not shown), such as a memory controller, to capture read data bits DQ0-31 in response to the DQS signal. During write operations, the read/write circuit 54 receives the DQS signal from the external controller in an optical receiver in the data converter 211 and latches write data bits DQ0-31 in response to the DQS signal.

The memory device 200 further includes a control logic 212 that optically receives a plurality of control and clocking bits from an optical control bus CONT typically applied by an external controller (not shown). The control and clocking bits are received in the memory device 200 through a control converter 213, which includes a plurality of optical receivers formed in the substrate 201. The control converter 213 may be formed in the same side of the semiconductor substrate as the control logic 212. The optical control and clocking bits are subsequently translated into corresponding electrical control and clocking signals in the control converter 213 and applied to the control logic and command decoder 212. The control signals include a chip select signal CS#, a write enable signal WE#, a column address strobe signal CAS#, and a row address strobe signal RAS#, while the clocking signals include a clock enable signal CKE# and complementary clock signals CLK, CLK#, with the "#" designating a signal as being active low. The external controller drives the control signals CS#, WE#, CAS#, and RAS# to particular states and supplies the corresponding address signals A0-AX on an optical address bus ADDR to apply a command to the memory device 200, such as a read, write, write partial, or load mode register command. The CKE signal enables clocking of the control logic and command decoder 212 by the clock signals CLK, CLK# and is utilized during self refresh operation of the memory device 200. The control logic and command decoder 212 also includes mode registers 216 that store information to define specific modes of operation of the memory device 200, such as the selection of a burst length, burst type, and CAS latency.

In response to the clock signals CLK, CLK#, the control logic and command decoder 212 latches and decodes the control signals portion of an applied command, and generates a sequence of clocking and control signals 214 that control the

components 204-55 to execute the function of the applied command. The control logic and command decoder 212 latches control signals and the address decoder 204 latches address signals A0-AX signals at positive edges of the CLK, CLK\* signals (*i.e.*, the crossing point of CLK going high and CLK# going low). The read/write circuit 202  
5 outputs read data bits DQ0-31 and latches write data bits DQ0-31 in response to both edges of the data strobe signal DQS, which has the same frequency as the CLK, CLK# signals. Thus, read data DQ0-31 and write data DQ0-31 are transferred from and to the memory device 200 at double the frequency of the clock signals CLK, CLK\*. The memory device 200 is therefore referred to as a double-data-rate device because the data  
10 bits DQ0-31 being transferred to and from the memory are transferred at double the rate at which commands are latched and at double the rate of a conventional SDRAM, which transfers data at a rate corresponding to the frequency of the applied clock signal.

In operation, the external controller applies optical address, control, and data bits to the memory device 200 over the address bus ADDR, control bus CONT, and  
15 data bus DATA, respectively, to control the operation of the memory. The address bus ADDR, control bus CONT, and the data bus DATA comprise any medium capable of carrying optical signals, for example free space or optical fibers. One of the major benefits of using optical signals as opposed to electrical signals to transmit the control, address and data bits is the avoidance of electrical conductors and the potential for cross  
20 talk which accompanies them. In addition, optical conductors are also beneficial in reducing noise. This is especially the case with optical fibers, which are much less susceptible to noise than conductive traces.

In a preferred embodiment, the control bus CONT, address bus ADDR, and data bus DATA include optical fibers embedded in a circuit board connector, such  
25 as that described in U.S. patent 6,233,376 to Uprgrove, incorporated herein by reference. Such a circuit board connector includes layers of optical fibers separated from each other by insulative layers. Additionally, electrical conductors may be formed in the connector and separated from each other, and from optical fibers, by insulating layers. In use, the electrical controller may be located on the connector and optically coupled to  
30 optical fibers formed therein. The memory device 200 can also be located on the connector, and its control converter 213, address converter 205 and data converter 211



may be optically coupled to optical fibers in the connector corresponding to the control bus CONT, address bus ADDR and data bus DATA, respectively. In this way, the controller can be on the same substrate as, and be optically coupled to, a plurality of memory devices 200. Alternately, the memory device 200 may be part of a memory  
5 module located on the connector, as will be discussed in more detail below.

The memory device 200 operates in the same way as previously described for the conventional DRAM 100 of Figure 1 during read and standard write operations. Briefly, during read operations, the external controller applies a read command to the memory device 200 in the form of appropriate optical address bits on  
10 the address bus ADDR and optical control bits on the control bus CONT. The control bits are received and converted into corresponding electrical signals by the address converter 205. The electrical address signals are then latched and decoded by the address decoder 204 and applied to the memory-cell array 208. Read data from the appropriate memory cells in the memory-cell array 208 is subsequently transferred  
15 through the internal data path 55 and read/write circuit 54 to the data converter 211 where it is translated into corresponding optical read data bits and transmitted to the external data bus DATA as optical read data bits DQ0-31.

During standard write operations, the external circuit applies a write command to the memory device 200 in the form of appropriate optical address bits and  
20 control bits on the ADDR and CONT buses, respectively, and also applies write optical data bits DQ0-31 and DQS signals on the data bus DATA. Once again, in response to the applied optical address signals, the address converter 205 receives and converts the optical address bits into corresponding electrical address signals. Using the electrical address signals, the address decoder 204 accesses the addressed memory cells in the  
25 memory-cell array 208. The read/write circuit 54 latches the applied write data bits DQ0-31 in response to the DQS signal, and transfers the latched write data words over the internal data path 55 to the addressed memory cells in the memory-cell array 208.

During both read and write operations, the control logic and command decoder 212 generates appropriate clocking and control signals 214 to control the  
30 address decoder 204, memory-cell array 208, and read/write circuit 54.

Figure 3 shows an alternate embodiment of the invention in which a plurality of memory devices 304-310, such as the memory device 200, are grouped together on a memory module 311. As illustrated, a controller 312 is coupled to the module 311 over an optical data bus DQ, an optical address bus ADDR, and an optical control bus CONT. As with the memory device 200 discussed above, the data bus DATA, control bus CONT, and the address bus ADDR may comprise fiber optic links, free space, optical paths formed in a substrate, or any suitable medium for communicating optical signals. The module 311 includes four memory devices 304-310, however a greater or lesser number of devices 304-310 may be coupled to the module 311. Each device 304-310 has an address converter 315, control converter 317 and data converter 319 operable to receive optical bits from the address bus ADDR, control bus CONT, and data bus DATA and convert the bits into corresponding electrical control, address and data signals. Each memory device 304-310 is then operable to apply the electrical control, address and data signals to an internal address decoder, control logic and command decoder, and read write circuit (not shown for the sake of clarity) as discussed above in Figure 2 in order access corresponding memory cells in a memory cell array (also not shown for the sake of clarity) on each memory device 304-310. Additionally, the data converter 319 is operable to receive electrical read data bits and transmit corresponding optical read data signals to the data bus DATA.

In the example of Figure 3, each memory device 304-310 receives two corresponding optical chip select bits CS1#-CS2# from the memory controller 312 over the CONT bus. During read and write operations the controller 312 applies a command to the memory devices 304-310 in the form of optical address bits on the address bus ADDR and optical control bits 326 along with the chip select bits CS1#-CS2# on the control bus CONT. These bits are received and decoded by control converters and address converters included in each device 304-310. The controller 312 activates one chip select bit CS1#-CS2# at a time and only the device 304-310 to which the unique chip select signal corresponds is activated. Once activated, the selected device 304-310 receives an ensuing sequence of optical control, address and data signals from the controller 312 instructing the device 304-310 to carry out a read or write sequence in the

same manner as discussed above. Once the particular cycle is completed, the controller uses the chip select signals CS1#-CS2# to select and enable another device 304-310 on the module 311 for a read or a write cycle.

Figures 4, 5A and 5B show alternate embodiments of the invention in which a plurality of memory devices 448 are grouped together on a memory module 450. Turning first to Figure 4, a system controller 460 is coupled to a memory module 450 through an optical link 465. It should be understood that more than one module 450 can be coupled to the optical link 465. The optical link 465 may comprise one or more optical fibers, free space, or optical paths formed in an insulative substrate, as discussed above. The controller 460 and the memory module 450 include an optical input/output port or separate input and output ports coupled to the optical link 465.

The memory module 450 includes a memory hub 470 for controlling access to 6 memory devices 448, which, in the example illustrated in Figure 4, are structurally and functionally the same as device 200 discussed in Figure 2. However, a fewer or greater number of memory devices 448 may be used. The memory hub 470 is coupled to each of the memory devices 448 through a bus system 475, which normally includes a control bus, an address bus and a data bus, and can comprise traces on the hub 470 operable to electrically couple the hub to the memory devices 448 or an optical link, or plurality of links, coupling the devices 448 to the hub 470.

The memory hub 470 can be implemented in several different embodiments. For example, as shown in the cross-sectional view of the memory module 450 in Figure 5A, in a first embodiment the memory hub 470 can include optical receivers and transmitters in the input/output port 502 operable to receive optical control, address and data bits from the optical link 465 and convert the optical bits into corresponding electrical control, address and data signals. The input/output port 502 can also be operable to receive electrical signals, convert them into corresponding optical bits, and transmit the optical bits to the controller 460 (not shown in Figure 5) over the optical link 465.

In this mode, the memory hub 470 is operable to communicate with the devices 448 through electrical signals coupled to the bus system 475. The devices 448 used in conjunction with such a hub 470 would have control, address and data

converters dissimilar from those discussed in Figure 1, however, since the signals being received by the devices would not have to be translated from optical bits to electrical signals. Thus optical receivers and transmitters would be omitted from the converters, and the control, address and data converters would comprise signal lines coupled to the  
5 corresponding lines of the bus system 475.

To communicate with the devices 448, the hub applies control, address and data signals to the bus system 475, with the appropriate memory device 448, or devices 448, being enabled by chip select signals contained within the control signal. In a write operation however, the control signal includes an additional write enable signal  
10 enabling the selected memory device 448 to accept data contained in the data signal and write it to an appropriate memory cell indicated by address information contained in the address signal.

Alternately, in another embodiment of the invention, the memory hub 470 could include a multiplexing function. After receiving a signal from the controller  
15 460 over the optic link 465 and converting it into electrical control, address and data signals as discussed above, the memory hub 470 subsequently examines the electrical control signal for information indicating which memory device 448 is to be accessed. Upon finding and decoding this information, the memory hub 470 applies the electrical control, address and data signals to an individual bus, or busses, in the bus system 475  
20 coupling the appropriate memory device 448 to the memory hub 470.

As with the aspect discussed above, if the control signal contains a write enable signal, the memory device 448 is enabled to accept data contained in the data signal and write it to the appropriate memory cells indicated by address information contained in the address signal. Otherwise, a read operation is initiated and appropriate  
25 memory cells in the memory device 448 are applied in a data signal over the individual bus in the bus system 475 coupling the memory device 448 to the memory hub 470. Once received in the memory hub 470, the data signal is subsequently converted into a signal suitable to be applied to the optical link 465, and the bits are transmitted to the controller 460 in the manner discussed above. It should be understood that in both  
30 aspects described above, the memory hub 470 may access a single bit from each memory device 448 or multiple bits as desired.

In another embodiment of the invention, the memory hub 470 communicates optically with the devices 448 as shown in the cross-sectional view of the memory module 450 in Figure 5B. For the sake of clarity, the hub 470 and devices 448 are shown in Figure 5B as being elevated from a top surface 501 of the memory module 450. It will be understood by those skilled in the art, however, that the hub 470 and the devices 448 could also rest flat on the surface 501 or be placed in indentations on the surface 501. Communications between the controller 460 (not shown in Figure 5B) and the hub 470 are accomplished in the same way as described above. However, once being received from the input/output port 502, the electrical control, address and data signals are developed in the hub 470 and converted into corresponding optical control, address and data bits at input/output terminals 504, 506 coupling the memory bus 475 to the memory hub 470.

As with the first embodiment described above, in order for the hub 470 to communicate optically with the devices 448, optical control, address and data bits are applied by the hub 470 over the bus system 475 to input/output ports 508/510 including optical receivers and transmitters on the memory devices 448. The appropriate memory device 448, or devices 448, are then enabled by chip select bits contained within the control bits. In a write operation however, the control bits include additional write enable bits enabling the selected memory device 448 to accept data contained in the data bits and write it to an appropriate memory cell indicated by address information contained in the address bits.

Alternately, the memory hub 470 could include a multiplexing function in which the memory hub 470 could examine the control signal received from the controller over the optical link 465 for information indicating which memory device 448 is to be accessed. Using this information, the memory hub 470 could apply the optical control, address and data bits to an individual bus in the bus system 475 coupling the appropriate memory device 448 to the memory hub 470.

As with the aspect discussed above, if the control signal contains write enable bits, the memory device 448 is enabled to accept data contained in the data bits and write it to the appropriate memory cells indicated by address information contained in the address bits. Otherwise, a read operation is initiated and data bits from

appropriate memory cells in the memory device 448 are applied as data signals over the individual bus in the bus system 475 coupling the memory device 448 to the memory hub 470. Once received in the memory hub 470, the data signals are subsequently converted into a signal suitable to be applied to the optical link 465, and  
5 the signal is transmitted to the controller 460, as discussed above. It should be understood that in both aspects described above, the memory hub 470 may access a single bit from each memory device 448 or multiple bits as desired.

A computer system 600 using the controller 460 and the memory module 450 of Figure 4 according to one example of the invention is shown in Figure 6. The  
10 computer system 600 includes a processor 604 for performing various computing functions, such as executing specific software to perform specific calculations or tasks. The processor 604 includes a processor bus 606 that normally includes an address bus, a control bus, and a data bus. The computer system 600 includes a system controller 607 that is coupled to the processor bus 606. The system controller 607 also includes the  
15 controller 460, which is, in turn, optically coupled to memory modules 450a-n through the optical link 465. However, it will be understood that the controller 460 may be external to the system controller 607 and coupled to it or some other component in the computer system 600, such as the processor 604. In addition, the computer system 600 includes one or more input devices 618, such as a keyboard, mouse or game controller,  
20 coupled to the processor 604 through the system controller 607 to allow an operator to interface with the computer system 600. Typically, the computer system 600 also includes one or more output devices 620 coupled to the processor 604 through the system controller 607, such output devices typically being a printer or a video terminal. One or more data storage devices 624 are also typically coupled to the processor 604  
25 through the system controller 607 to allow the processor 604 to store data or retrieve data from internal or external storage media (not shown). Examples of typical storage devices 624 include hard and floppy disks, tape cassettes, and compact disk read-only memories (CD-ROMs). The processor 604 is also typically coupled to cache memory 626, which is usually static random access memory ("SRAM").

30 From the foregoing it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration,

various modifications may be made without deviating from the spirit and scope of the invention. Accordingly, the invention is not limited except as by the appended claims.

## CLAIMS

1. A memory device, comprising:
  - a semiconductor substrate;
  - an address converter fabricated in the substrate, the address converter being operable to receive and convert optical address signals into corresponding electrical address signals;
  - an address decoder fabricated in the semiconductor substrate, the address decoder being coupled to the address converter to receive the electrical address signals from the address converter;
  - a data converter fabricated in the substrate, the data converter being operable to receive and convert optical write data signals into corresponding electrical write data signals and to receive and convert electrical read data signals into corresponding optical read data signals;
  - a read/write circuit fabricated in the semiconductor substrate, the read/write circuit being coupled to the data converter to receive the electrical read data signals from the data converter and to couple the electrical write data signals to the data converter;
  - a control signal converter fabricated in the substrate, the control signal converter being operable to receive and convert optical control signals into corresponding electrical control signals;
  - a control logic unit fabricated in the semiconductor substrate, the control logic unit being coupled to a control converter fabricated in the substrate; and
  - a memory-cell array fabricated in the semiconductor substrate, the memory-cell array being coupled to the address decoder, control circuit, and read/write circuit.
2. The memory device of claim 1 wherein the memory device comprises a dynamic random access memory.



3. The device of claim 1 wherein the optical control signals comprise clock enable signals, row address strobe signals, column address strobe signals, write enable signals and chip select signals.

4. The device of claim 1 wherein the data converter comprises a plurality of optical transmitters and receivers fabricated in the substrate.

5. The device of claim 1 wherein the control signal converter and address converter each comprise a plurality of optical receivers fabricated in the substrate.

6. The device of claim 1 wherein the data converter comprises a cavity type laser operable to transmit optical signals.

7. The device of claim 1 wherein the control signal, address and data converters comprise optical Darlington transistors.

8. The device of claim 1 wherein the control signal, address and data converters comprise optical field effect transistors operable to receive optical signals.

9. A memory module, comprising:  
an insulative substrate;  
a plurality of memory devices mounted on the substrate, each memory device comprising:

a semiconductor substrate;

a plurality of electrical input and output terminals fabricated in the semiconductor substrate including electrical data terminals operable to output read data signals and input write data signals, and electrical address and control terminals operable to input address and control signals;

a plurality of optical receivers fabricated in the semiconductor substrate coupled to corresponding data, control and address terminals, the receivers being

operable to receive optical signals and translate the optical signals into corresponding electrical signals;

a plurality of optical transmitters fabricated in the semiconductor substrate coupled to corresponding data terminals, the optical transmitters being operable to receive read data signals and translate the read data signals into corresponding optical read data signals; and

a plurality of optical paths coupled to the optical receivers and transmitters.

10. The memory module of claim 9 wherein the plurality of optical transmitters are operable to transmit signal packets corresponding to electrical signals input to the optical transmitters.

11. The memory module of claim 9 wherein the control signals comprise clock enable signals, row address strobe signals, column address strobe signals, write enable signals and chip select signals.

12. The memory module of claim 9 wherein the memory devices comprise dynamic random access memories.

13. The memory module of claim 9 wherein the optical receivers comprises cavity type lasers operable to transmit optical signals.

14. The memory module of claim 9 wherein the optical paths are fabricated in the insulative substrate.

15. The memory module of claim 9 wherein the optical receivers comprise optical Darlington transistors.

16. The memory module of claim 9 wherein the optical receivers comprise optical field effect transistors operable to receive optical signals.

17. The memory module of claim 9 wherein each optical path comprises a plurality of optical links.

18. The memory module of claim 9 wherein each optical path comprises a fiber optic link.

19. The memory module of claim 9 wherein each optical path comprises free space.

20. The memory module of claim 9 wherein the optical paths comprise control, address and data busses.

21. The memory module of claim 9 wherein the insulative substrate comprises a plurality of optical paths embedded within the insulative substrate.

22. A memory module, comprising:  
an insulative substrate;  
a plurality of memory devices mounted on the substrate, each memory device comprising:

a semiconductor substrate;

a plurality of electrical input and output signal lines fabricated in the semiconductor substrate including electrical data signal lines operable to output electrical read data signals and input electrical write data signals, and electrical address and control signal lines operable to input electrical address and control signals;

a plurality of optical receivers fabricated in the semiconductor substrate coupled to corresponding data, control and address signal lines, the receivers being operable to receive optical signals and develop corresponding electrical signals; and

a plurality of optical transmitters fabricated in the semiconductor substrate coupled to corresponding data signal lines, the optical transmitters being operable to receive electrical read data signals and develop corresponding optical read data signals;

a memory hub mounted on the insulative substrate, the memory hub having an input/output port and a plurality of input and output terminals including terminals outputting optical write data signals, terminals inputting optical read data signals, and terminals outputting optical command and address signals, the memory hub being operable to receive input signals coupled to the input/output port and to apply corresponding optical signals to the terminals of the memory hub, the memory hub being further operable to receive optical signals at the terminals of the memory hub and to apply output signals to the input/output port; and

a plurality of optical paths coupling the terminals of the memory hub to the optical transmitters and receivers of the memory devices.

23. The memory module of claim 22 wherein the input/output port is operable to receive optical input signals, and transmit optical output signals.

24. The memory module of claim 23 wherein the optical input signals, comprise control, address and write data signals, and the optical output signals comprise read data signals.

25. The memory module of claim 22 wherein the input/output port is operable to receive electrical input signals, and transmit electrical output signals.

26. The memory module of claim 25 wherein the electrical input signals, comprise control, address and write data signals, and the electrical output signals comprise read data signals.
27. The memory module of claim 22 wherein the memory devices comprise dynamic random access memory devices.
28. The memory module of claim 22 wherein the optical transmitters comprise cavity type lasers operable to transmit optical signals.
29. The memory module of claim 22 wherein the optical receivers comprise optical Darlington transistors.
30. The memory module of claim 22 wherein the optical receivers comprise optical field effect transistors operable to receive optical signals.
31. The memory module of claim 22 wherein each optical path comprises a plurality of optical links.
32. The memory module of claim 22 wherein each optical path comprises a fiber optic link.
33. The memory module of claim 22 wherein each optical path comprises free space.
34. The memory module of claim 22 wherein each optical path comprises control, address and data busses.
35. The memory module of claim 22 wherein the optical paths are fabricated in the insulative substrate.

36. The memory module of claim 22 wherein the memory hub applies optical hub control, address and data signals to each memory device on the module simultaneously.

37. The memory module of claim 22 wherein the memory hub detects device address information in the input signal and applies optical control, address and data signals to a corresponding memory device on the module.

38. The memory module of claim 22 wherein the insulative substrate comprises a plurality of optical paths embedded within the insulative substrate.

39. A memory module, comprising:  
an insulative substrate;  
a plurality of memory devices mounted on the substrate, each memory device comprising:

a semiconductor substrate; and

a plurality of electrical input and output signal lines fabricated on the semiconductor substrate including electrical data signal lines operable to output electrical read data signals and input electrical write data signals; and electrical address and control signal lines operable to input electrical address and control signals;

a memory hub mounted on the insulative substrate, the memory hub having an optical input/output port and a plurality of electrical input and output terminals including terminals outputting electrical write data signals, terminals inputting electrical read data signals, and terminals outputting electrical command and address signals, the memory hub being operable to receive optical input signals coupled to the input/output port and to apply corresponding electrical signals to the terminals of the memory hub, the memory hub being further operable to receive electrical signals at the terminals of the memory hub and to apply optical output signals to the input/output port; and

a plurality of signal paths coupling the terminals of the memory hub to the data, address and control signal lines on the memory devices.

40. The memory module of claim 39 wherein the optical input signals, comprise optical control, address and write data signals, and the optical output signals comprise optical read data signals.

41. The memory module of claim 39 wherein the memory devices comprise dynamic random access memory devices.

42. The memory module of claim 39 wherein each signal path comprises a plurality of conductive traces.

43. The memory module of claim 39 wherein each signal path comprises control, address and data busses.

44. The memory module of claim 39 wherein the memory hub is operable to apply electrical hub control, address and data signals to each memory device on the module simultaneously.

45. The memory module of claim 39 wherein the memory hub is operable to detect device address information in the input signal and apply electrical control, address and data signals to a corresponding memory device on the module.

46. The memory module of claim 39 wherein the insulative substrate comprises a plurality of optical paths embedded within the insulative substrate, and further wherein at least one optical path is coupled to the optical input/output port.

47. A memory module, comprising:

an insulative substrate having a plurality of optical paths extending therethrough;

a plurality of memory devices mounted on the substrate, each memory device comprising:

a semiconductor substrate;

a plurality of electrical input and output signal lines fabricated in the semiconductor substrate including electrical data signal lines operable to output electrical read data signals and input electrical write data signals, and electrical address and control signal lines operable to input electrical address and control signals;

a plurality of optical receivers fabricated in the semiconductor substrate operably coupling the optical paths in the insulative substrate with corresponding data, control and address signal lines, the receivers being operable to receive optical signals and generate corresponding electrical signals;

a plurality of optical transmitters fabricated in the semiconductor substrate operably coupling the optical paths in the insulative substrate with corresponding data signal lines, the optical transmitters being operable to receive electrical read data signals and generate corresponding optical read data signals; and

a memory hub mounted on the insulative substrate, the memory hub having an input/output port and a plurality of optical input terminals and optical output terminals including terminals outputting optical write data signals, terminals inputting optical read data signals, and terminals outputting optical command and address signals, the terminals being coupled to corresponding optical paths in the substrate and being operable to transmit the optical command address and write data signals to the optical receivers in the memory devices, the terminals being further operative to receive the optical read data signals from the optical transmitters in the memory devices, the memory hub being operable to receive optical input signals coupled to the input/output port and to apply corresponding optical signals to the terminals of the memory hub, the memory hub being further operable to receive optical



signals at the terminals of the memory hub and to apply optical output signals to the input/output port.

48. The memory module of claim 47 wherein the optical input signals, comprise control, address and write data signals, and the optical output signals comprise read data signals.

49. The memory module of claim 47 wherein the memory devices comprise dynamic random access memory devices.

50. The memory module of claim 47 wherein the optical transmitters comprise cavity type lasers operable to transmit optical signals.

51. The memory module of claim 47 wherein the optical receivers comprise optical Darlington transistors.

52. The memory module of claim 47 wherein the optical receivers comprise optical field effect transistors operable to receive optical signals.

53. The memory module of claim 47 wherein each optical path comprises a plurality of optical links.

54. The memory module of claim 47 wherein each optical path comprises a fiber optic link.

55. The memory module of claim 47 wherein each optical path comprises free space.

56. The memory module of claim 47 wherein each optical path comprises control, address and data busses.

57. The memory module of claim 47 wherein the memory hub is operable to apply optical hub control, address and data signals to each memory device on the module simultaneously.

58. The memory module of claim 47 wherein the memory hub is operable to detect device address information in the optical input signal coupled to the input/output port and apply optical control, address and data signals to a corresponding memory device on the module.

59. A computer system, comprising:  
a data input device;  
a data output device;  
a processor coupled to the data input and data output devices;  
a insulative substrate;  
a controller coupled to the substrate and electrically coupled to the processor, the controller being operable to receive optical data signals and apply optical control, address and data signals to an optical path at a controller port;

a plurality of memory devices mounted on the substrate, each memory device comprising:

a semiconductor substrate;

a plurality of electrical input and output signal lines fabricated in the semiconductor substrate including electrical data signal lines operable to output electrical read data signals and input electrical write data signals; and electrical address and control signal lines operable to input electrical address and control signals;

a plurality of optical receivers fabricated in the semiconductor substrate coupled to corresponding data, control and address signal lines, the receivers being operable to receive optical signals and generate corresponding electrical signals; and

a plurality of optical transmitters fabricated in the semiconductor substrate coupled to corresponding data signal lines, the optical transmitters being

operable to receive electrical read data signals and generate corresponding optical read data signals;

a memory hub mounted on the insulative substrate, the memory hub having an input/output port and a plurality of input and output terminals including terminals outputting optical write data signals, command signals and address signals, and terminals inputting optical read data signals, the memory hub being operable to receive input signals coupled to the input/output port and to apply corresponding optical signals to the terminals of the memory hub, the memory hub being further operable to receive optical signals at the terminals of the memory hub and to apply output signals to the input/output port; and

a plurality of optical paths coupling the terminals of the memory hub to the optical transmitters and receivers of the memory devices.

60. The computer system of claim 59 wherein the optical paths are embedded within the insulative substrate.

61. The computer system of claim 59 wherein the input/output port is operable to receive optical input signals, and transmit optical output signals.

62. The computer system of claim 61 wherein the optical input signals, comprise control, address and write data signals, and the optical output signals comprise read data signals.

63. The computer system of claim 59 wherein the input/output port is operable to receive electrical input signals, and transmit electrical output signals.

64. The computer system of claim 63 wherein the electrical input signals, comprise control, address and write data signals, and the electrical output signals comprise read data signals.

65. The computer system of claim 59 wherein the memory devices comprise dynamic random access memory devices.

66. The computer system of claim 59 wherein the optical transmitters comprise cavity type lasers operable to transmit optical signals.

67. The computer system of claim 59 wherein the optical receivers comprise optical Darlington transistors.

68. The computer system of claim 59 wherein the optical receivers comprise optical field effect transistors operable to receive optical signals.

69. The computer system of claim 59 wherein each optical path comprises a plurality of optical links.

70. The computer system of claim 59 wherein each optical path comprises a fiber optic link.

71. The computer system of claim 59 wherein each optical path comprises free space.

72. The computer system of claim 59 wherein each optical path comprises control, address and data busses.

73. The computer system of claim 59 wherein the memory hub is operable to apply optical hub control, address and data signals to each memory device on the module simultaneously.

74. The computer system of claim 59 wherein the memory hub is operable to detect device address information in the input signal and apply optical control, address and data signals to a corresponding memory device on the module.

75. A method of communicating control and address signals to and/or from a memory device, comprising:

coupling optical signals corresponding to control and address signals to the memory device;

receiving the optical control and address signals in the memory device;

developing electrical control and address signals on the memory device corresponding to the optical control and address signals; and

accessing a memory location within the memory device in accordance with the control and address signals.

76. The method of claim 75, further comprising:

coupling optical write data signals corresponding to write data signals to the memory device;

receiving the optical write data signals in the memory device;

developing electrical write data signals on the memory device corresponding to the optical write data signals; and

writing data to the memory location.

77. The method of claim 75, further comprising:

reading data from a memory location;

developing optical read data signals on the memory device corresponding to the optical read data; and

coupling the optical read data signals from the memory device.

78. The method of claim 75 wherein the act of coupling optical signals corresponding to control and address signals to the memory device comprises coupling control and address signals over at least one optical fiber.

79. The method of claim 75 wherein the acts of coupling optical signals corresponding to control and address signals to the memory device comprises coupling control and address signals over free space.

80. The method of claim 75 wherein the act of coupling optical signals corresponding to control and addresses signals to the memory device comprises coupling optical signals corresponding to the control and address signals to the device over an optical path embedded in a substrate.

81. The method of claim 80 wherein the act of coupling optical signals corresponding to control, address and write data signals to the memory device over an optical path in a substrate comprise coupling control, address and data signals over at least one optical fiber embedded in the substrate.

82. The method of claim 75 wherein the act of coupling optical signals to the memory device comprises coupling optical signals to the memory device in the form of optical signal packets.

83. A method of communicating control and address signals to a memory device, comprising:

coupling optical signals corresponding to control and address signals from a memory hub to the memory device;

receiving the optical control and address signals in the memory device;

developing electrical control and address signals in the memory device corresponding to the optical control and address signals; and

accessing a memory location within the memory device in accordance with the control and address signals.

84. The method of claim 83, further comprising:

coupling optical write data signals corresponding to write data signals from the memory hub to the memory device;

receiving the optical write data signals in the memory device;

developing electrical write data signals on the memory device corresponding to the optical write data signals; and

writing data to the memory location.

85. The method of claim 83, further comprising:

reading data from a memory location;

developing optical read data signals on the memory device corresponding to the optical read data; and

coupling the optical read data signals from the memory device to the memory hub.

86. The method of claim 83 wherein the act of coupling optical signals corresponding to control and address signals to the memory device comprises coupling control and address signals over at least one optical fiber.

87. The method of claim 83 wherein the act of coupling optical signals corresponding to control and address signals to the memory device comprises coupling control and address signals over free space.

88. The method of claim 83 wherein the act of coupling optical signals corresponding to control and address signals to the memory device further comprises coupling optical signals corresponding to the control and address signals to the hub over an optical path in a substrate.

89. The method of claim 88 further comprising coupling optical control and address signals from a controller to the hub over an optical path.

90. The method of claim 89 wherein the act of coupling optical control and address signals from a controller to the hub over an optical path comprises coupling optical signals between the hub and controller in the form of optical signal packets.

91. The method of claim 88 wherein the acts of coupling optical signals corresponding to control and address signals to the hub over an optical path in a substrate comprise coupling control and address over at least one optical fiber.

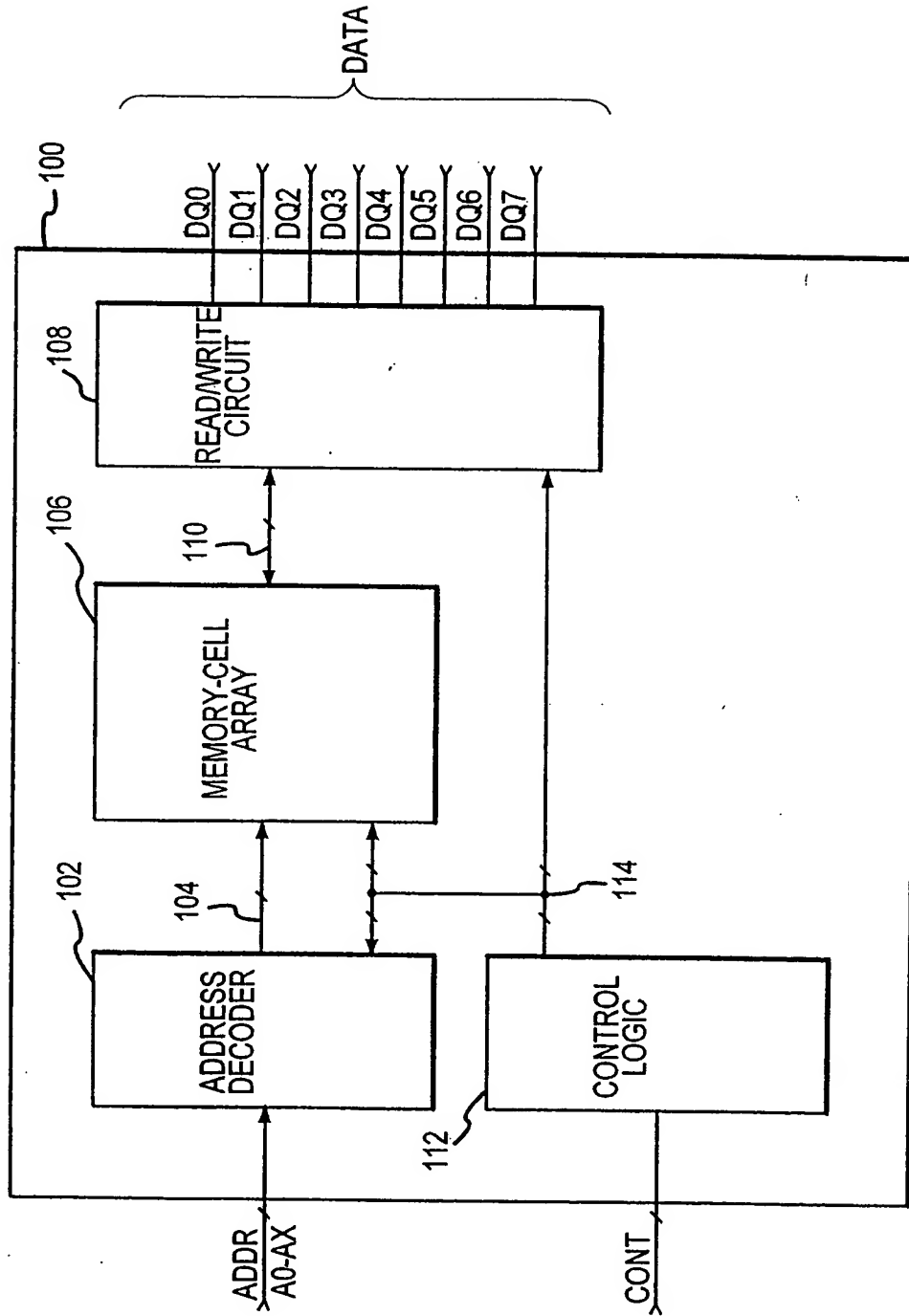
92. The method of claim 83 wherein the act of coupling optical signals between the memory hub and the memory device comprises coupling optical signals, to and from the memory device in the form of optical signal packets.



SYSTEM AND METHOD FOR OPTICALLY INTERCONNECTING MEMORY  
DEVICES

ABSTRACT OF THE DISCLOSURE

A memory device includes a semiconductor substrate in which memory circuitry has been fabricated. An address converter and a control signal converter are coupled to an address decoder and control logic, respectively. The address and control converters are operable to receive and convert optical address and control signals, respectively, into corresponding electrical address signals applied to the address decoder and control signals applied to the control logic. A read/write circuit on the substrate is coupled to a data converter formed in the substrate. The data converter is operable to receive and convert optical write data signals into corresponding electrical data signals to be applied to the read/write circuit and to receive and convert electrical read data signals into corresponding optical read data signals.



(PRIOR ART)  
FIG. 1

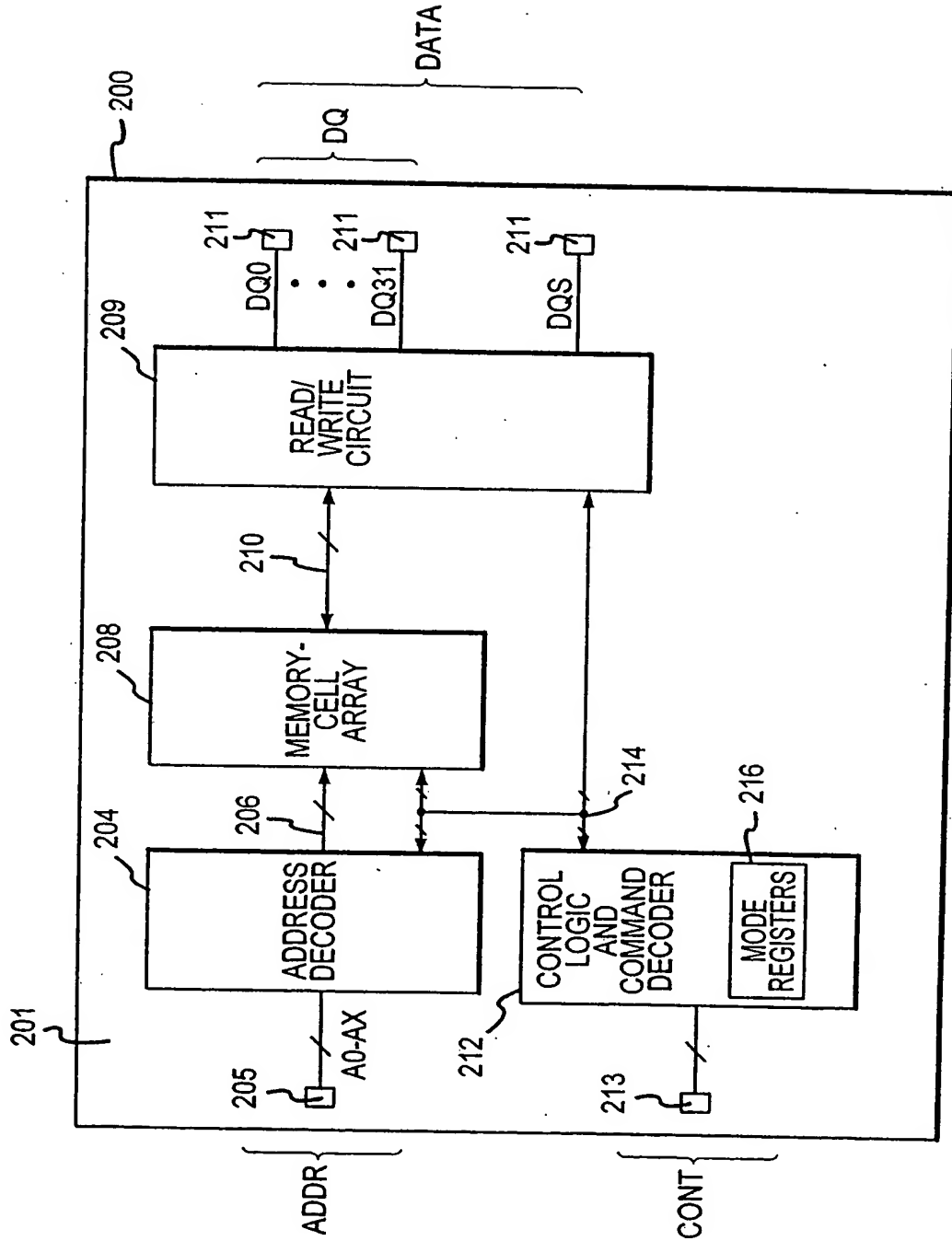
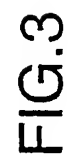


FIG.2



**FIG. 3**

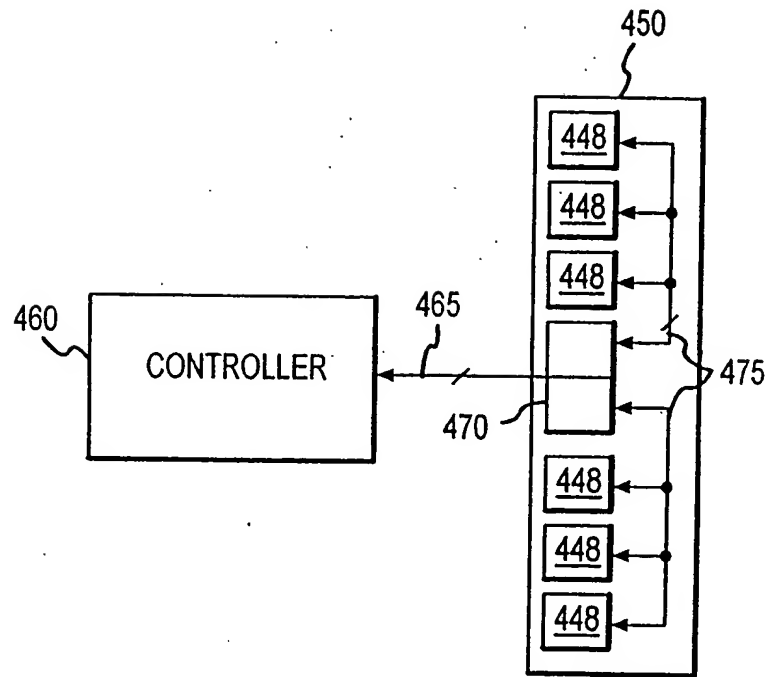


FIG.4

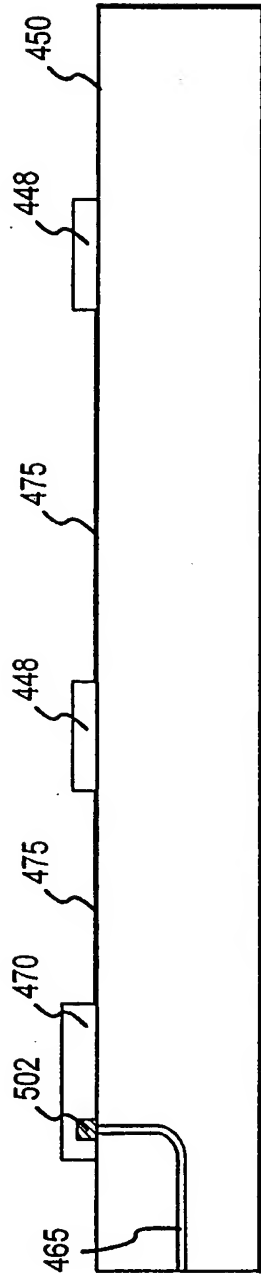


FIG. 5A

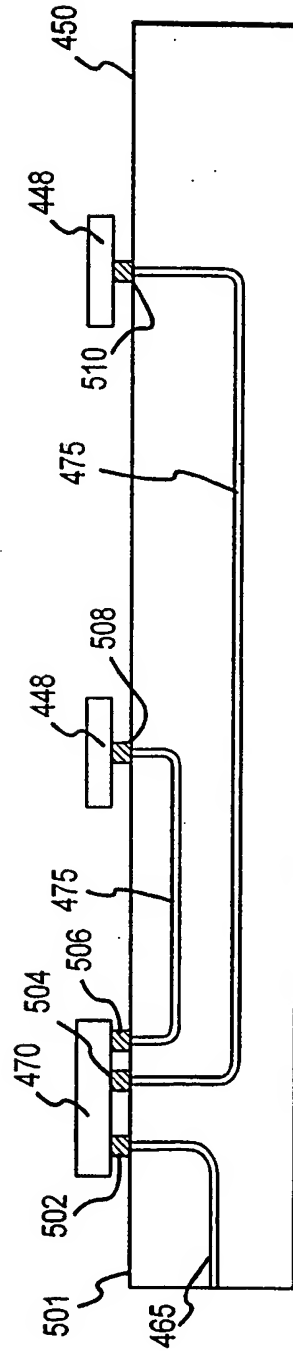


FIG. 5B

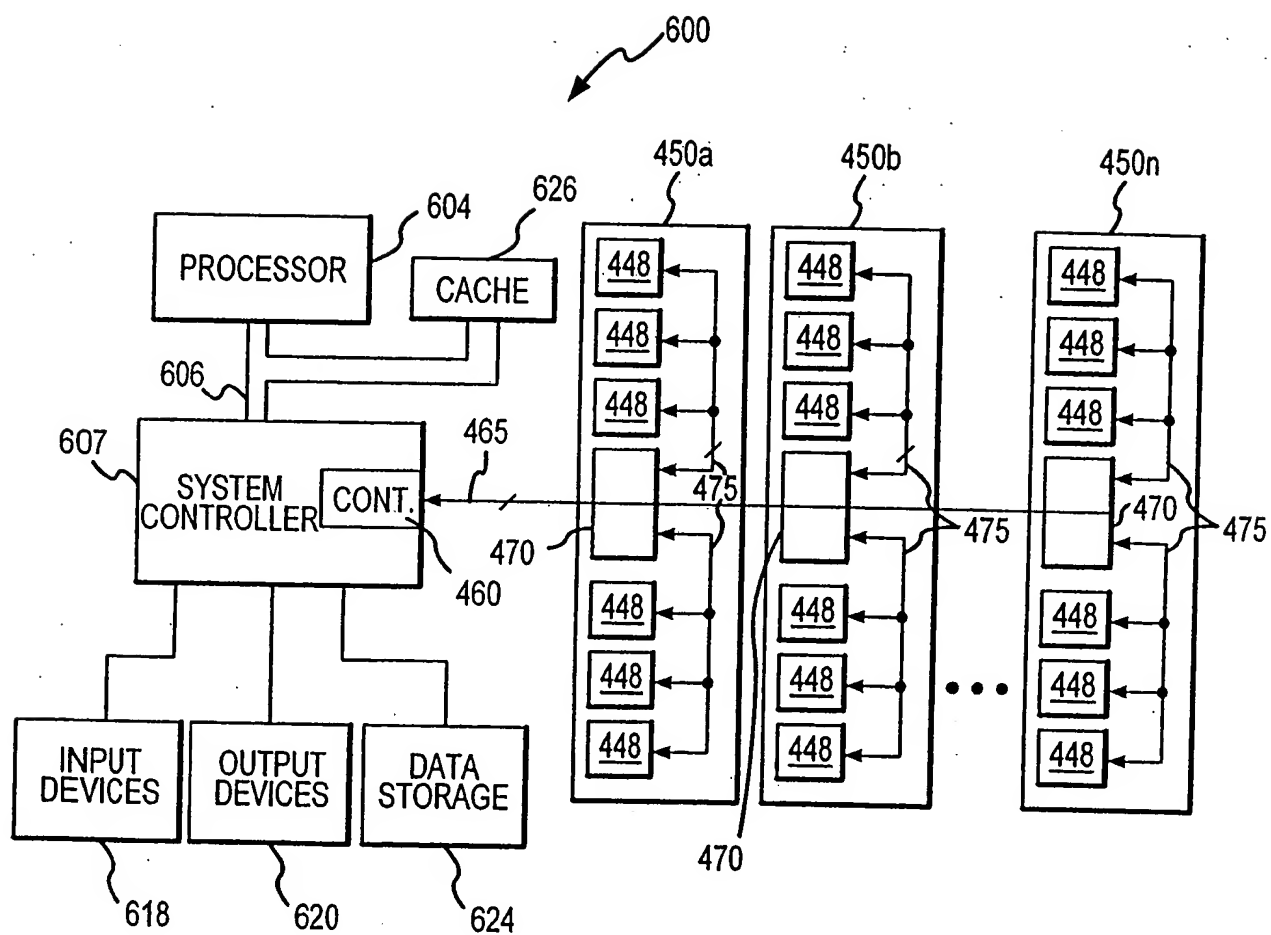


FIG.6

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